

Evaluation of Acoustic Channel Capacity for Complex Piping Topology

*Transmission of Information by Acoustic Communication along Metal Pathways
in Nuclear Facilities*

Nuclear Science and Engineering Division

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Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities

prepared by

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Abstract

Transmission of information using elastic waves on existing metallic pipes provides an alternative communication option for a nuclear facility. The advantages of this approach consist of transmitting information through physical barriers, such as the containment building wall. In addition, this approach provides physical cybersecurity since the pipe becomes an analog communication channel which is difficult to eavesdrop on and difficult to sever. In prior work, a laboratory bench-scale system consisting of a six foot-long straight section of nuclear grade stainless steel pipe and high-temperature ultrasonic LiNbO_3 transducers was assembled. The lab systems was used for communication protocol development and preliminary data transmission demonstration. Next phase of project development involves deployment of the ultrasonic communication system in a representative environment. Mechanisms Engineering Test Loop (METL) facility at ANL was chosen as a viable candidate for communication system demonstration. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. This report describes preliminary studies on transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90° was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and LiNbO_3 transducers, with the signals recorded with previously developed LabView interface. Preliminary results have shown significant dispersion of transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was initially investigated for transmission through solids, and demonstrated for signals transmitted over the bent pipe. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle.

1. Introduction

1.1. Background

Integration of advanced communication technologies into nuclear facility operation has the potential for enhancing safety and efficiency of the existing fleet of aging light water reactors, as well those of future advanced reactors [Korsah 2017]. Conventional wired and wireless communication systems face implementation challenges at nuclear facilities due to the presence of thick reinforced concrete walls with steel liners, such as those of the containment building. In addition, concerns related to security vulnerabilities in conventional communication networks have to be addressed when developing communication systems for nuclear facilities. In this report, we describe recent progress on developing a wireless communication system for a nuclear facility, in which information is carried with elastic waves propagating on metallic pipes. Such communication system would take advantage of the existing piping infrastructure to transmit information in and out of containment building, as shown in Figure 1 [Argonne 2018]. Furthermore, information sent over this system would only be accessible through direct physical contact with the pipes, thus establishing a protection layer against unauthorized eavesdroppers. The pipe is difficult to sever, compared to conventional communication cables, which provides a measure of physical cybersecurity against insider threats.

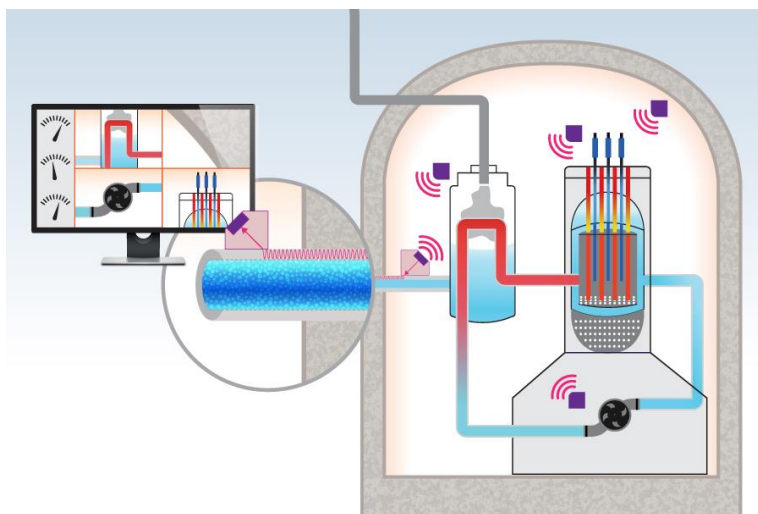


Figure 1 – Proposed acoustic communication system at a nuclear facility would transmit information on steel pipes already in place for nuclear reactor operation [ANL 2018]

The charging line of CVCS (chemical and volume control system) was previously identified as a promising channel for acoustic information transmission in and out of the containment building [Heifetz 2018, Heifetz 2019]. A laboratory bench-scale prototype of a CVCS pipe, consisting of a six-foot long stainless steel schedule 160 pipe with 2.375in outer diameter and stainless steel baffle plates was developed for proof-of-principle demonstrations [Heifetz 2018]. Amplitude shift keying (ASK) communication protocol was developed and implemented using GNURadio

software defined radio (SDR) environment. Prior results included demonstration of information transmission, such as images, text files, and sound, Data transmission on heated pipes was demonstrated using a text file and a 90KB image of Argonne logo. In particular, transmission with 10Kbps bitrate of data was achieved on the pipe heated to 50°C and 150°C, which represented communication during normal and post-accident environment at the facility. Preliminary communication studies were conducted with ultrasonic paintbrush transducers. To perform ultrasonic data transmission at temperatures up to 150°C and above, we have utilized custom-made high-temperature compatible LiNbO₃ ultrasonic transducers, originally developed at Argonne for liquid sodium flow metering application at EBR-II.

1.2. Introduction

We have identified the Mechanisms Engineering Test Loop (METL) facility at Argonne as a viable candidate for demonstration of the ultrasonic communication in a representative environment. METL facility is an intermediate-scale liquid metal experimental facility that provides purified R-grade sodium to various experimental test vessels to test components that are required to operate in a prototypical advanced reactor environment [Kultgen 2018]. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. This report describes preliminary studies on transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90° was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and LiNbO₃ transducers, with the signals recorded with previously developed LabVIEW interface. Preliminary results have shown significant dispersion of transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was initially investigated for communication through solids [Saniie 2019], proposed and demonstrated for signals transmitted over the bent pipe. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle.

2. Data Transmission on Bent Pipe

2.1. Analysis of piping topology in a representative environment

Stainless steel piping in a METL facility at Argonne provides a viable platform for proof-of-principle demonstration of the ultrasonic communication system in a prototypical advanced reactor environment. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. Examples of piping bent at 90° are shown in Figure 2 [Kultgen 2018]. Figure 2(a) displays a 3D computer generated model of representative piping elements, and Figure 2(b) shows a photograph of a section of METL piping. The bent section of piping is formed by welding of straight sections with an elbow. Prior studies on this project have been focused on coupling carrier elastic shear waves into metal pipes and developing of communication protocol on data transmission. A straight section of piping has been used for proof-of-principle laboratory studies. Before embarking on ultrasonic signal transmission over the complex piping network at METL facility, a preliminary study evaluating signal transmission losses due to piping bends is required.

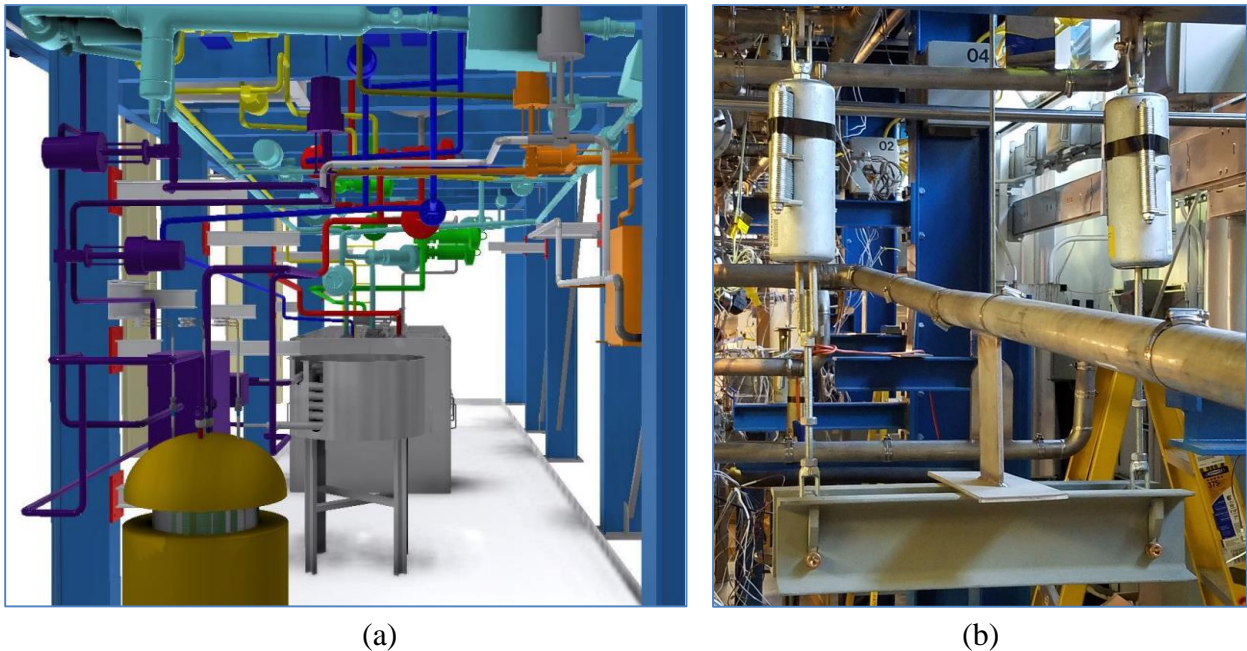


Figure 2 – (a) A 3D model of the uninsulated elements of piping system (b) Photograph of a section of METL piping [Kultgen 2018]

2.2. Development of a bent pipe test article

A test article consisting of a stainless steel pipe bent at 90° was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight three-foot-long pipes to an elbow at the ANL Central Shops. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies (schedule 160 pipe with 2.375in outer diameter). Figure 3(a) shows the blueprint drawing of the

straight pipes and the elbow section. The edges of the components were chamfered to insert straight piping sections into the elbow. Welding was performed to the same leak-proof quality as typical for piping in METL facility. After welding, the outer surface was grinded to achieve visibly smooth finish. Figure 3(b) shows the schematics of the welded piping laboratory assembly.

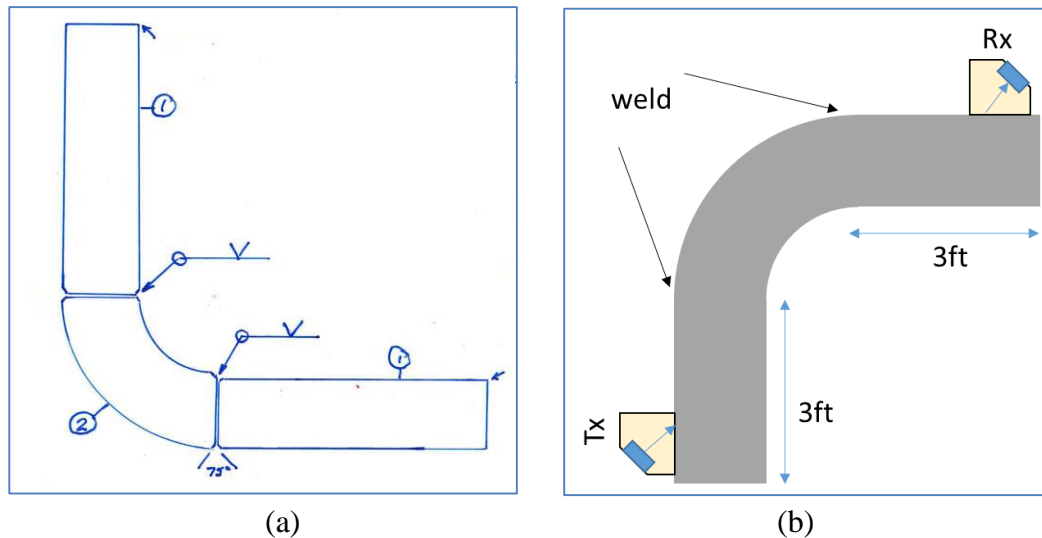


Figure 3 – (a) Blueprint drawings of straight sections and elbow (b) Schematics of welding piping assembly

The photograph of welded piping assembly installed on an optical bench in the laboratory is shown in Figure 4. Angled wedge-mounted piezoelectric (PZT) and LiNbO₃ transducers were coupled to the pipe to conduct signal transmission studies. Distances between the transducers were kept approximately the same as in the previous studies involving ultrasonic signal transmission on a straight pipe.



Figure 4 – Bent piping assembly in the laboratory

2.3. COMSOL modeling of ultrasonic signal transmission on a bent pipe

COMSOL Solid Mechanic Module computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across the bent piping structure. In the computer model, angled wedge mounted PZT generates longitudinal waves at the contact surface with acrylic wedge. COMSOL direct solution of elastodynamic equations leads to generation shear waves at the acrylic/metal pipe surface. In previously developed COMSOL model, PZT was modeled as iron block vibrating at an ultrasonic frequency perpendicular to the acrylic wedge surface [Young 2018]. The amplitude of displacement of the iron block is on the order of a micrometer. However, because of explicit modeling of PZT mechanical vibration, this COMSOL model required very fine meshing, which demanded significant computing resources. For example, modeling wave propagation on a 5in-long section of piping required 40GB of memory. Because of computer workstation memory limitations, only short piping sections could be modeled with this approach. To improve computational efficiency of COMSOL simulations and to model larger piping structures, we developed a new approach, which allowed reducing COMSOL model memory size from 40GB to 3GB for the same problem. In the new approach, the longitudinal waves are modeled as a boundary load applied to the acrylic wedge surface, which would in contact with PZT in the experiment. However, as could be seen in the graphics in Figure 5, PZT structure is absent from COMSOL model. As in the previous models, refracted shear waves are generated at the boundary of acrylic wedge and stainless steel pipe through direct solution of elastodynamic equations in COMSOL. The new approach allows performing computer simulations with a coarser mesh, while still maintaining sufficiently high resolution. Because of reduced memory requirement, the new approach allows to model much larger piping structures.

In this project, we modeled a bent piping structure with a 90° turn, which is shown in Figure 5. All parameters of the metallic structure in the COMSOL model were the same as those of the experimental assembly in Figure 4, except that the straight piping sections were 30cm each. Reducing the size piping structure allowed performing COMSOL simulations faster and with less computer memory, while still capturing all essential physics of the problem. Longitudinal ultrasonic waves at 500KHz frequency were coupled as boundary pressure load to the acrylic wedge angled at 45° . This angle exceeds the first critical angle of 27.6° for the acrylic/stainless steel interface. Therefore, the incident longitudinal wave is expected to be mode-converted into a shear wave, which would subsequently propagates down the stainless steel pipe. This is, in fact, what we have observed in the output of COMSOL simulations shown in several panels in Figure 5. Elastic waves are visualized with pseudo-color plot of pressure distribution. Amplitude of the pressure is amplified compared to actual experimental values to enhance elastic wave visibility.

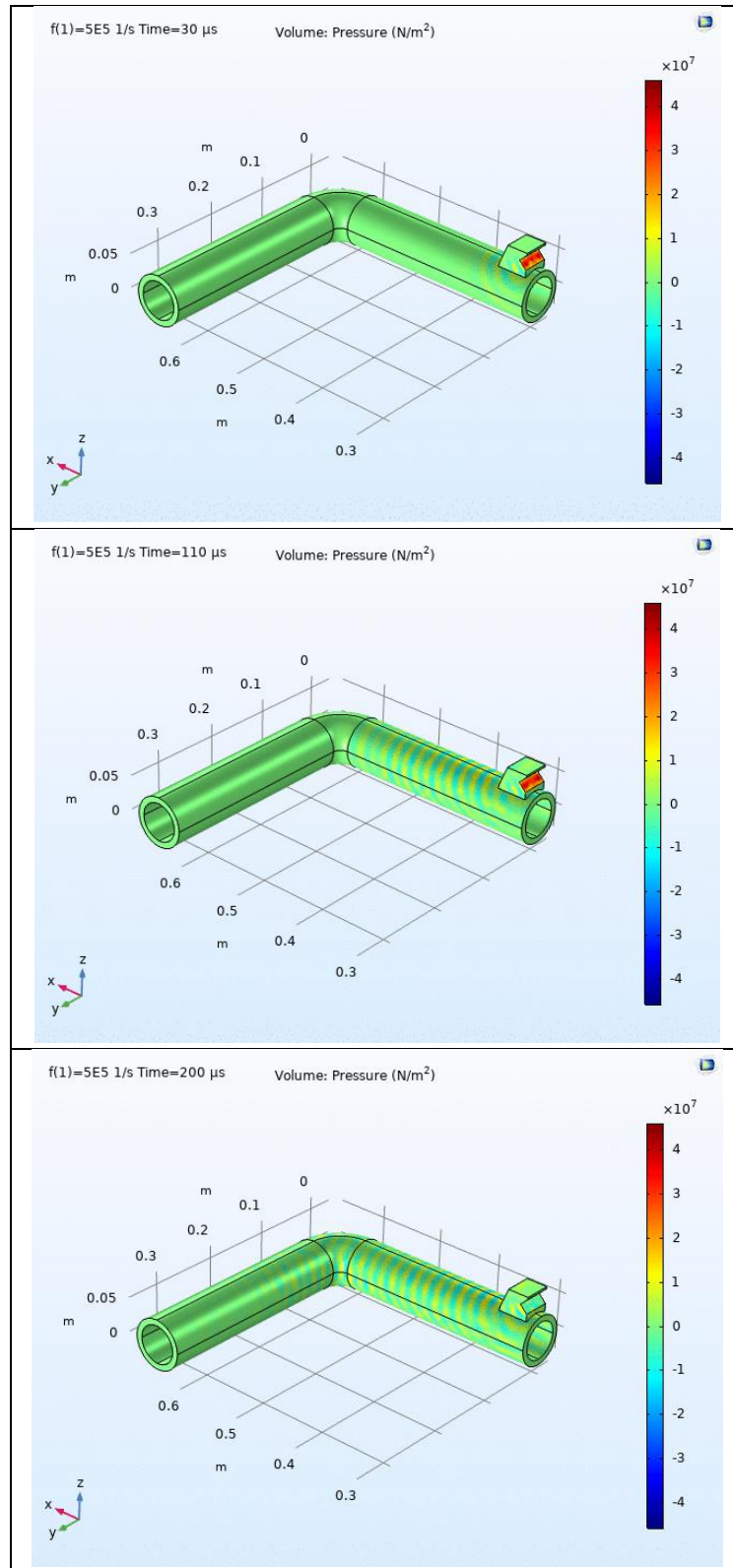


Figure 5 – Propagation of 500KHz refracted shear wave on a metallic pipe visualized with pseudo-color map of pressure distribution at 30 μs , 110 μs , and 200 μs

The top panel in Figure 5 shows pressure distribution $30\mu\text{s}$ after the start of the simulations, when refracted shear wave is coupled into the pipe. The middle panel in Figure 5 shows pressure distribution after $110\mu\text{s}$, when the wave reaches the elbow. Note that the propagation distance to the geometrical center of the bent section is slightly larger than 30cm because the elbow increases the length of the overall piping structure by approximately 10cm. Since the shear wave velocity in stainless steel is 3100m/s , in the $110\mu\text{s}$ the propagation distance is 34cm, which is qualitatively in agreement with COMSOL simulations. The longitudinal wave velocity is 5790m/s , so that in $110\mu\text{s}$ the longitudinal wave would have traversed 63cm distance, which is almost the entire bent piping structure. This is not observed in COMSOL simulations in Figure 5. Therefore, these observations confirm that COMSOL model generates refracted shear waves on a pipe. The bottom panel in Figure 5 shows pressure distribution at $200\mu\text{s}$ after the start of simulations. At this point, ultrasonic shear wave has propagated across the elbow and reached the middle of second straight section. This confirms qualitatively that ultrasonic waves travel across the piping bends. Quantitative analysis of ultrasonic wave attenuation will be performed in later studies.

2.3. Characterization of ultrasonic signal transmission on a bent pipe

Preliminary evaluation of ultrasonic signal transmission across the bent piping laboratory test article pictured in Figure 4 was performed with a pair of angled-wedge mounted 500KHz PZT's and high-temperature LiNbO_3 transducers operating at 750KHz. The PZT's were mounted on 45° angled wedge transducers to generate refracted shear wave. The total length of the bent piping structure is approximately seven feet, with the combined length of six feet of straight sections, and approximately one foot length of the elbow. The transmitted signal was amplified with 50dB power amplifier, and the received signal was amplified with 20dB low noise amplifier. The signals were acquired with LabVIEW software interface. Figure 6 shows received $100\mu\text{s}$ -duration pulse, transmitted with PZT's across the bent piping assembly. Delay time is approximately $700\mu\text{s}$, which is consistent with the shear wave travel velocity of 3100m/s . One can observe in Figure 6 that the received signal is significantly distorted and dispersed in time, with effective temporal duration of the pulse stretched to $500\mu\text{s}$. We hypothesize that such distortions are due to scattering of ultrasonic waves by welds at the piping joints. The ripples in the received signal are separated by approximately $100\mu\text{s}$ time delays, which is consistent with the time it takes the shear wave to traverse the length of the elbow between the weld joints. Similar results were observed when transmitting signals with LiNbO_3 transducers.

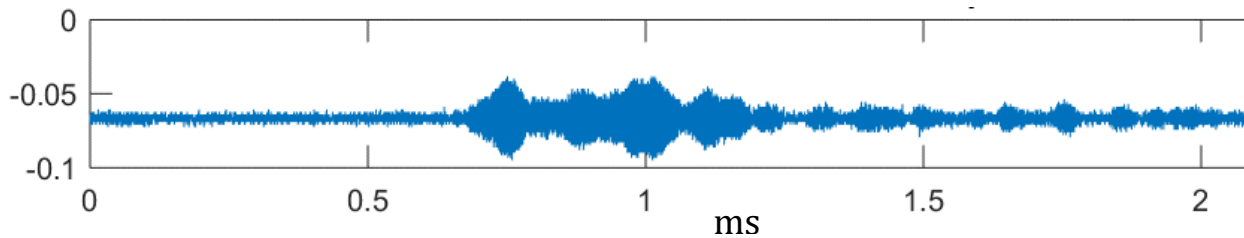


Figure 6 – Transmission of $100\mu\text{s}$ pulse with 500KHz PZT's across bent piping assembly

3. Matched Filtering via Time Reversal Modulation

As described in Section 2, transmission of ultrasonic signals over a bent pipe results in significant temporal distortion of the received signals compared to those transmitted over the same length on a straight pipe. This distortion presents a significant challenge to communication due to effective decrease in bitrate and possible increase in inter-symbol interference. Since signal distortions are likely due to welds at piping joints, which are difficult to model in advance, we chose to develop a matched filter based on time reversal modulation (TRM) signal processing technique.

3.1. Theory of time reversal modulation

Time-reversal modulation, also called phase conjugation in optics, is a general method for compensation of distortions in signal caused by propagating through random scattering media. The basic principle of this method consists of cross correlating a signal with its time-reversed replica, which results in elimination of random noise. Mathematical theory of matched filter based on TRM consists of using a waveform sampler at time $t = T$, which contains signal $s(t)$ with amplitude a and noise $n(t)$ with variance σ_n . The instantaneous ratio of signal power to average noise power is

$$\left(\frac{S}{N} \right)_T = \frac{a^2(t)}{\sigma_n^2(t)} \quad (1)$$

The signal and noise can be related to frequency response of the filter transfer function $H(f)$ as

$$a(t) = \int_{-\infty}^{\infty} H(f)S(f)e^{j2\pi ft} df \quad (2)$$

$$\sigma_n^2 = \frac{N}{2} \int_{-\infty}^{\infty} |H(f)|^2 df \quad (3)$$

Where $S(f)$ is the spectrum of the signal. We wish to find the transfer function $H(f)$ which maximizes the ratio

$$\left(\frac{S}{N} \right)_T = \frac{\left| \int_{-\infty}^{\infty} H(f)S(f)e^{j2\pi ft} df \right|^2}{\frac{N_0}{2} \int_{-\infty}^{\infty} |H(f)|^2 df} \quad (4)$$

This ratio is maximized when

$$S(f) = H(f)e^{-j2\pi ft} \quad (5)$$

So that

$$\max\left(\frac{S}{N}\right)_T = \frac{2}{N} \int_{-\infty}^{\infty} |H(f)|^2 df \quad (6)$$

In time domain

$$h(t) = s(T - t) \quad (7)$$

That is, the impulse response of a filter produces the maximum signal to noise ratio when the filter is the mirror image of the message signal in time domain.

Implementation of TRM filter in ultrasonic communication on pipes would require channel calibration prior to communication session. That is, a copy of calibration ultrasonic signal transmitted over the pipe has to be sent back to the transmitter through some other means. It is assumed that the piping channel will not change over the course of the communication session. Any change in the channel will require re-calibration of the TRM filter.

3.2. Application of time reversal modulation to signal transmission over bent pipes

TRM filter concept for acoustic communications was initially developed and tested using solid bodies as channels [Saniie 2019], and subsequently applied to signals transmitted across the laboratory bent piping test article. Figure 7 shows the results of filtering of signals transmitted and received with LiNbO₃ transducers. These transducers generate ultrasonic shear waves at 750KHz frequency. Shear waves are generated due to appropriate orientation of the LiNbO₃ crystal. Results in different panels in Figure 7 are shown for ultrasonic pulses with 200μs, 100μs, 50μs, and 10μs temporal duration, respectively. The graphics in the left column of Figure 7 show the original received signal with significant temporal spreading and distortion. The pulse showing up near the origin of the time axis in each figure is the RF pickup of the transmitted ultrasonic signal, which is an artifact of the laboratory-based communication system. The right column in Figure 7 contains graphics showing application of the TRM filter to each respective signal. In each case, the TRM filter was developed by time reversing the waveform in the left column. After application of TRM, each pulse has signal to noise ratio SNR>2, which allows for unambiguous detection of the pulses. It should be noted that capability of receiving signals with 10μs temporal duration can lead to implementation of communication system with 100Kbps bitrate. This would constitute an order of magnitude improvement of communication bitrate of 10Kbps reported in our most recent work.

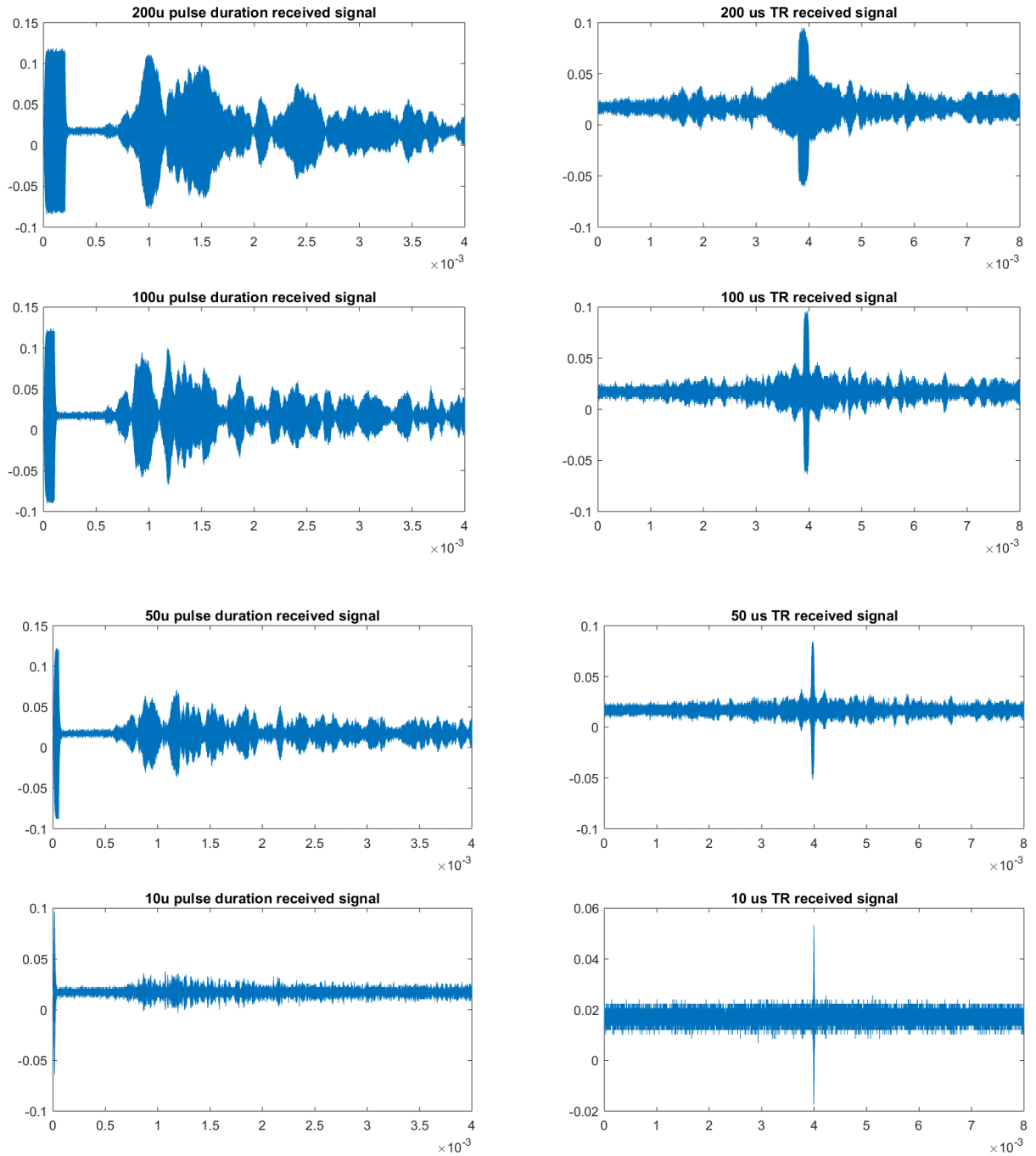


Figure 7 – TRM filter applied to 200 μ s, 100 μ s, 50 μ s, and 10 μ s pulses transmitted with LiNbO₃ across bent piping assembly

To evaluate applicability of TRM to high bitrate communication system, we have applied TRM to improvement of SNR for a train of 10 bits, each represented by pulses with $10\mu\text{s}$ temporal duration. The pulses were transmitted on bent piping test article with LiNbO_3 transducers. The train of pulses obtained after matched filtering with TRM is shown in Figure 8. All pulses have $\text{SNR} > 2$, which allows unambiguous detection of logical “1” and logical “0”. This result demonstrates that communication at 100Kbps is, in principle, possible. Further work on high bitrate information transmission would involve incorporating TRM module into GNURadio communication protocol [Shribak 2018].

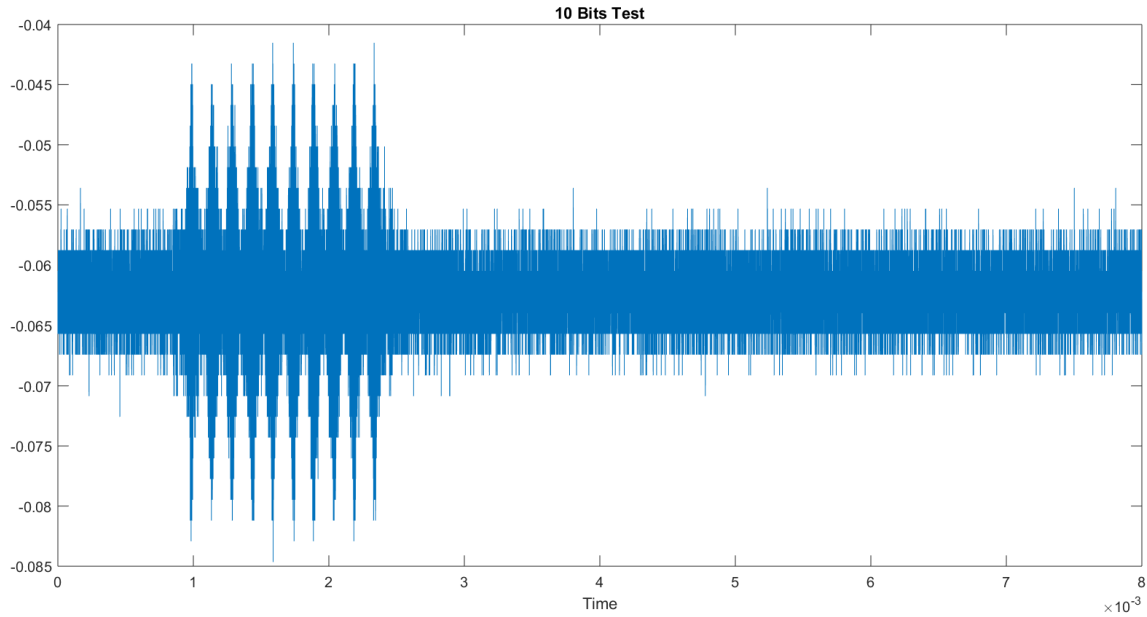


Figure 8 – TRM filter applied to a sequence of ten pulses, each of $10\mu\text{s}$ duration, transmitted with LiNbO_3 transducer across bent piping assembly

4. Conclusions

Research efforts described in this report involved analysis of ultrasonic signal transmission over complex piping manifolds. The work was conducted in preparation for demonstration of the ultrasonic communication system performance in a representative environment. Mechanisms Engineering Test Loop (METL) facility at ANL was chosen as a viable candidate for communication system demonstration. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. This report describes preliminary studies on transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90° was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and LiNbO₃ transducers, with the signals recorded with previously developed LabView interface. Preliminary results have shown significant dispersion of transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was proposed and demonstrated for signals transmitted over the bent pipe. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle. Next steps on the project will involve developing communication protocol for transmission of images across bent piping assembly. This would require modification of the existing GNURadio communication protocol to incorporate TRM filter in the information modulation scheme.

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